LJ-00-07C

SOUTHWEST FISHERIES SCIENCE CENTER

NATIONAL MARINE FISHERIES SERVICE · SOUTHWEST FISHERIES SCIENCE CENTER · P.O. BOX 271 LA JOLLA, CA 92038

RECEIVED
AUG 24 2000
NMFS/HONOLULU LAB
DIRECTOR'S OFFICE

JUNE 2000

MEASUREMENTS OF THE LOW FREQUENCY COMPONENTS OF ACTIVE AND PASSIVE SOUNDS PRODUCED BY DOLPHINS

by

Paul E. Nachtigall, Whitlow W.L. Au, Jeffrey L. Pawloski,
Kimberly Andrews, and Charles W. Oliver

ADMINISTRATIVE REPORT LJ-00-07C

"This report is used to ensure prompt dissemination of preliminary results, interim reports, and special studies to the scientific community. The material is not ready for formal publication since the paper may later be published in a modified form to include more recent information or research results. Abstracting, citing, or reproduction of this information is not allowed. Contact author if additional information is required."

MEASUREMENTS OF THE LOW FREQUENCY COMPONENTS OF ACTIVE AND PASSIVE SOUNDS PRODUCED BY DOLPHINS

Paul E. Nachtigall
Whitlow W.L.Au
Jeffrey L. Pawloski
Kimberly Andrews

Marine Mammal Research Program
Hawaii Institute of Marine Biology
University of Hawaii

and

Charles W. Oliver

Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
P.O. Box 271, La Jolla, California 92038

in accordance with
order number 40JGNF800279
issued 07/16/98
NOAA
National Marine Fisheries Service
La Jolla, California 92038-0271

Explanatory Note

This report is one in a series on the potential for technology applications to enhance efficiency in commercial fisheries, reduce the catch of non-targeted species, and provide new tools for fishery assessments in support of the NMFS strategic goals to build sustainable fisheries and recover protected species. We hope the distribution of this report will facilitate further discussion and research into the application's potential usefulness, but should not be construed as an endorsement of the application by NMFS.

Pursuant to changes in the Marine Mammal Protection Act in 1988, the NMFS' SWFSC began a series of ETP-related studies in 1990, focused on developing and evaluating methods of capturing yellowfin tuna, which do not involve dolphins. This series of studies has been conducted within the SWFSC's Dolphin-Safe Research Program. Studies on the potential use of airborne lidar (LIght Detection And Ranging) systems began in 1991, and studies on low-frequency acoustic systems to detect fish schools at ranges much greater than currently possible were initiated during 1995. In addition to their use as an alternative to fishing on dolphins, these systems have potential to increase the efficiency of the fishing operations by locating fish schools not detectable by customary visual means, and as a fishery-independent tool to conduct population assessments on pelagic fish. They also have potential to adversely impact marine animals.

During 1991-1998, the Dolphin-Safe Research Program investigated, through a series of contracts and grants, five airborne lidars: 1) the NMFS-developed "Osprey" lidar (Oliver et al., 1994), 2) the Kaman Aerospace Corporation's FISHEYE imaging lidar (Oliver and Edwards 1996), 3) the NOAA Environmental Technology Laboratory's Experimental Oceanographic Fisheries Lidar (Churnside et al., 1998), 4) the Arete Associates 3D Streak-Tube Imaging Lidar, and 5) the Detection Limited's lidar. An initial study on the potential effects of airborne lidars on marine mammals was completed during 1998 (Zorn et al., 1998).

During 1991-1998 the Dolphin-Safe Research Program completed, through a series of contracts and grants, acoustic system studies on 1) the acoustic target strength of large yellowfin tuna schools (Nero 1996), 2) acoustic detection parameters and potential in the eastern tropical Pacific Ocean (Rees 1996), 3) the design of two towed acoustic systems (Rees 1998, Denny et al., 1998), 4) measurements of swimbladder volumes from large yellowfin tuna (Schaefer and Oliver 1998), 5) the potential effects of low-frequency sound on marine mammals (Ketten 1998), and 6) two studies on the potential for tuna to detect low-frequency sounds produced by dolphins (Finneran et al., 1998; Nachtigall et al., 2000).

Chuck Oliver
Dolphin-Safe Research Program
Southwest Fisheries Science Center
P.O. Box 271
La Jolla, California 92037

Dolphin-Safe Research Program Detection Technology Reports

Armstrong, W.A. and C.W. Oliver. 1996. Recent use of fish aggregating devices in the eastern tropical Pacific tuna purse-seine fishery: 1990-1994. Southwest Fisheries Science Center Admin. Rpt. LJ-96-02. 47p.

Churnside, J.H., J.J. Wilson, and C.W. Oliver. 1998. Evaluation of the capability of the experimental oceanographic fisheries lidar (FLOE) for tuna detection in the eastern tropical Pacific. NOAA Tech. Memo. ERL ETL-287. Environmental Technology Laboratory, Boulder, CO. 74p.

Denny, G.F., K.E. deVilleroy, and P.K. Simpson. 1998. Long-range tuna school detection sonar system design specification. Scientific Fishery Systems, Inc., Anchorage, AK. Southwest Region Admin. Rpt. SWR-98-01. 38p plus appendices.

Edwards, E.F., C.W. Oliver, and J.E. Sisson. 1995. 2nd Dolphin-safe research planning workshop: (March 14-17, 1994) report and recommendations. Southwest Fisheries Science Center Admin. Rpt. LJ-95-05. 42p.

Finneran, J.J., C.W. Oliver, K.M. Schaefer, and S.H. Ridgway. 1998. Yellowfin tuna (*Thunnus albacares*) detection of low frequency sounds produced by bottlenose dolphins (*Tursiops truncatus*). Southwest Fisheries Science Center Admin. Rpt. LJ-99-06C. 34p.

Finneran, J.J., C.W. Oliver, K.M. Schaefer, and S.H. Ridgway. 2000. Source levels and estimated yellowfin tuna (*Thunnus albacares*) detection ranges for dolphin jaw pops, breaches, and tail slaps. *J. Acoust. Soc. Am.* 107(1): 649-656.

Griffis, A.J. 1999. Demonstration and evaluation of the streak tube imaging lidar for use in bycatch reduction. (Areté Associates Incorporated Final Report ART-99-578-001-TR pursuant to National Oceanic and Atmospheric Administration Grant No. NA77FD0045). Southwest Region Admin. Rpt. SWR-99-02. 104p.

Ketten, D. 1998. Marine mammal auditory systems: a summary of audiometric and anatomical data and its implications for underwater acoustic impacts. NOAA-TM-NMFS-SWFSC-256. 74p.

Nachtigall, P.E., W.L. Au, J.L. Pawloski, K. Andrews, and C.W. Oliver. 2000. Measurements of the low frequency components of active and passive sounds produced by dolphins. Southwest Fisheries Science Center Admin. Rpt. LJ-00-07C. 20p.

Nero, R. W. 1996. Model estimates of acoustic scattering from schools of large yellowfin tuna. Report NRL/MR/774-95-7708. Naval Research Lab. Stennis Space Center, MS. 21p.

Oliver, C., W. Armstrong, and J. Young 1994. "Development of an airborne LIDAR system to detect tunas in the eastern tropical Pacific purse-seine fishery" NOAA-TM-NMFS-SWFSC-204. 65p.

Oliver, C.W. and Edwards, E.F. 1996. Dolphin-Safe Research Program Progress Report II (1992-1996). Southwest Fisheries Science Center Admin. Rpt. LJ-96-13. 91p.

Rees, C. D. 1996. Modeling of acoustic detection of yellowfin tuna in the eastern tropical Pacific fishery area. Southwest Fisheries Science Center, La Jolla, CA. 83p plus appendices.

Rees, C. D. 1998. Active towed-array acoustic system design study for yellowfin tuna in the eastern tropical Pacific fishery area. NOAA-TM-NMFS-SWFSC-251. 65p plus appendices.

Schaefer, K. M. and C. W. Oliver. 1998. Shape, volume, and resonance frequency of the swimbladder of yellowfin tuna (*Thunnus albacares*). Southwest Fisheries Science Center Admin. Rpt. LJ-98-09C. 27p.

Schaefer, K. M. and C. W. Oliver. 2000. Shape, volume, and resonance frequency of the swimbladder of yellowfin tuna (*Thunnus albacares*). *Fish. Bull.* 98(2): 364-374.

Summers, B. and G. Dillard. 1995. Radar location of tuna. SPAWARSYSGEN SAN DIEGO, Code 7501, San Diego, CA. 92152. 35p.

Zorn, H.M., J.H. Churnside, and C.W. Oliver. 1998. Laser safety thresholds for cetaceans and pinnipeds. Southwest Fisheries Science Center Admin. Rpt. LJ-98-10C. 21p.

Zorn, H.M., J.H. Churnside, and C.W. Oliver. 2000. Laser safety thresholds for cetaceans and pinnipeds. *Mar. Mamm. Sci.*, 16(1): 186-202.

Table of Contents

	Page
Title page	i
Explanatory Note	ii
Table of Contents	v
Introduction	1
Methods	3
Results	5
Discussion	6
References	8
Table 1. Sounds produced by dolphins (from Wartzog and Ketten, 1999).	11
Figure 1. Overall layout of dolphin and whale pens at the Hawaii Institute of Marine Biology	12
Figure 2. Peak-to-Peak source levels for 10 dolphin breaches.	13
Figure 3. Time display of a breach sound and its corresponding spectrogram.	14
Figure 4. Peak-to-Peak source levels from the sounds of 10 tail slaps.	15
Figure 5. Time display of a dolphin slapping its tail and the corresponding spectrogram.	16
Figure 6. The RMS source level of the recordings of 27 dolphin whistles.	17
Figure 7. Time display of the envelope and corresponding spectrogram of two dolphin whistles.	18
Figure 8. Time display and corresponding spectrogram of a recorded dolphin jaw-clap.	19
Appendix 1. Digital files from recordings of breaches, tail-slaps, whistles, and jaw-claps obtained from a bottlenose dolphin on April 22 and May 4, 1999. These data are binary, 2-bytes per point digitized at 44.1 kHz with Cool Edit. The custom-built hydrophone assembly has a sensitivity of -172 dB re V/μPa and is flat to 200 kHz.	20

MEASUREMENTS OF THE LOW FREQUENCY COMPONENTS OF ACTIVE AND PASSIVE SOUNDS PRODUCED BY DOLPHINS

Paul E. Nachtigall, Whitlow W.L.Au, Jeffrey L. Pawloski, Kimberly Andrews
Marine Mammal Research Program
Hawaii Institute of Marine Biology
University of Hawaii

and

Charles W. Oliver
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
P.O. Box 271, La Jolla, California 92038

In the eastern tropical Pacific Ocean, yellowfin Tuna, *Thunnus albacares*, commonly associate with a variety of odontocete cetaceans including the spinner dolphin, *Stenella longirostris*, and the pan-tropical spotted dolphin, *Stenella attenuata* (Perrin, 1969). Tuna fishermen frequently exploit this association by visually detecting the dolphins. The air-breathing dolphins remain closer to the surface and can be seen from a greater distance than the tuna (National Research Council, 1992). The association between tuna and dolphins may be related to a common food source (Perrin *et al.*, 1973; Scott & Cattanach, 1998), but the relative acuity of tuna sensory abilities, which must facilitate tuna-dolphin association, has not been critically examined.

Because there is a strong tuna-dolphin association, Schaefer & Oliver (2000) suggested there must be some dominant sensory cue that allows the tuna and dolphins to maintain the contact. Given that it is likely that much of the prey capture by the dolphins occurs it night, and at considerable depth, it seems reasonable that the tuna sense the presence of the dolphins acoustically rather than visually. In a classic experiment, Iverson (1967) trained two captive yellowfin to swim between two nets if a sound was presented and to swim straight if no sound was presented. Data from this behavioral audiogram experiment demonstrated that tuna heard best (e.g., most sensitive) between 200 and 800 Hz, and rapidly degraded above 1000 Hz. No measures of hearing of tuna for sounds above 2000 Hz were reported. Because most sounds produced by dolphin whistles and

clicks are generally higher than 2000 Hz (Wartzog & Ketten, 1999), we examined sounds produced by dolphins that might be heard by tuna. While there are limited data available about tuna auditory capabilities and thresholds, it is likely tuna may be capable of hearing some portion of the sound produced as dolphin whistles, echolocation clicks, or tail and body slaps.

While tuna hearing has not been tested at frequencies above 2 kHz, and clupeids are evolutionary distant from scombrids, Popper (1997) recently demonstrated that a clupeid prey, American Shad, *Alosa sapidissima*, of the bottlenose dolphin, *Tursiops truncatus*, can detect sounds up to 180 kHz with somewhat better detection in the areas of maximum frequency for echolocating dolphins (Au, 1974; 1993). Popper speculated that the fishes' ability to detect these ultrasonic signals may be an example of convergent evolution, similar to that of moths and other insects that have evolved the ability to detect the echolocation calls of predatory bats. While large tuna are not prey of small dolphins, they are prey of larger echolocating predators (Brill *et al.*, 1992; Thomas *et al.*, 1988) including the False killer whale, *Pseudorca crassidens* (Seifert, 1999). Perhaps more importantly, tuna and dolphins share common small fish prey (Perrin *et al.*, 1973) suggesting some mutual advantage must be present to cause the association between tuna and dolphins.

Sounds produced by wild spinner and spotted dolphins and closely related species are presented in Table 1. This data summary, taken from a recently written chapter by Wartzog & Ketten (1999), is primarily comprised of animal signals recorded in the field. There are a number of difficulties with data historically collected in the field, because both amplitude and frequency of acoustic signals are very difficult to accurately measure. First, there is a difficulty determining the actual source level (the amplitude of the sound produced at its source) from the measured received level (the level of the signal received at the hydrophone placed in the water to make the recordings). Since sounds, particularly at higher frequency, rapidly diminish in amplitude with distance, the actual intensity of the sound produced by the animal is difficult to precisely determine unless recorded directly in front of the animal's head at a known distance. Second, highly directed, high

frequencies produced in dolphin echolocation beam patterns (Au, 1980), are difficult to precisely determine because the measured frequency of the click is very much dependent on where within the beam pattern one is measuring. Examples of these difficulties can be seen by examination of the data collected from wild bottlenose dolphins (Table 1). Only the clicks collected by Au *et al.* (1974) and Au (1993) provide accurate amplitude and frequency data taken from a dolphin echolocating in its natural environment. The data reported by Dierks *et al.* (1971) and Evans (1973) were properly gathered but both source level and frequencies are dramatically reduced, most likely due to the fact that they were gathered in tanks (Nachtigall *et al.*, 1994).

To ascertain accurate acoustical data on the amplitude and frequency of sounds produced by spinner and spotted dolphins, one must capture the animals, maintain them in a natural seawater open environment, train them to complete echolocation tasks and to produce other natural sounds under stimulus control, and accurately place hydrophone receivers to record the signals. While there are no spinner or spotted dolphins in captivity available for acoustic research, there is a fine background of valid acoustic measures of the echolocation signals of the Atlantic bottlenose dolphin (Nachtigall & Moore, 1988; Au, 1993), and captive bottlenose dolphins are maintained in a natural environment at the Hawaii Institute of Marine Biology (HIMB), Coconut Island, Kaneohe Bay Hawaii.

The purpose of this study was to obtain accurate acoustic measures of whistle, tail slap, and breaching sounds produced by bottlenose dolphins. We speculate that these sounds are similar, in frequency and amplitude, to sounds produced by the spinner and spotted dolphins that associate with tuna in the eastern tropical Pacific Ocean.

Methods

The subject animal, a female adult Pacific bottlenose dolphin, *Tursiops truncatus*, named Kolohe weighed 178 Kg, measured 2.51 m in length, and was captured off the coast of Oahu Hawaii in 1987. She is owned by the U.S. Navy's Marine Mammal Program in San Diego and loaned to the University of Hawaii for scientific research

purposes. The animal is housed at the Marine Mammal Research Program's floating pen facilities on the leeward side of Coconut Island in Kaneohe Bay, Hawaii. A diagram of the floating pen facility is presented in Fig. 1. Sounds produced as whistles, tail slaps, and breaches were recorded during sessions on either April 22, 1999 or May 4, 1999. Two spontaneously produced jaw claps, produced when Kolohe vigorously clapped her jaws together, were also serendipitously recorded.

The animal was trained, over a period of months, to produce a variety of sounds based on signals given by the trainer. Stimulus control was established for emitting whistles, slapping the tail on top of the water, and jumping out of the water (breaching). The animal was trained to station at a fixed position and maintain a consistent orientation to the hydrophone while recordings were obtained for tail slaps and whistles, thus assuring a known distance between source and receiver. All sound-producing behaviors occur naturally, both in the wild and in captive situations. Breaching was deemed especially important given the similarity between this behavior and the active leaping and spinning exhibited by wild spinner dolphins

All measurements were conducted with a specially constructed hydrophone having a spherical piezoelectric element that is flat to approximately 200 kHz. The hydrophone was connected to a variable gain filter and signals were recorded using a Sony DAT-8 recorder with a fixed gain at unity. Hydrophone depth was 1 meter for all measurements. A 2 meter horizontal separation distance was maintained between the hydrophone and the dolphin's tail during tail-slap measurements, and between the hydrophone and the dolphin's head during measurements of jaw claps and whistles. Breaching sounds were measured with the hydrophone between 2.6 and 3.6 m from the point of impact assuring an accurate measure of the sound and the wetness of the person recording. Signals were clearly audible above the relatively low ambient noise level produced by snapping shrimp (Au & Banks, 1998). The recorded data were digitized and subsequently analyzed with the 'Cool Edit' program.

Results

Because the desired sound-producing behaviors are within the dolphin's natural behavioral repertoire, the animal was rapidly trained to whistle, tail slap and breach in response to simple visual signals. Sounds produced during breaches produced the highest amplitudes. Recorded peak-to-peak sound pressure levels for each of ten breaches are shown in Fig. 2. The source level is the sound pressure level referenced to a distance of 1 m from the point of impact where the animal landed on the water after jumping into the air. The animal normally landed on its side after its snout touched a ball suspended 12 feet above the water. Sound pressure levels ranged between 168 and 181 dB re 1 μPa with an average source level of 175.5 dB with a standard deviation of 4.01 dB. Recognizing that dB is a logarithmic scale and that there can not be a true standard deviation which would require a linear scale, the numbers provided are for general descriptive purposes of the variability and not for statistical precision.

An example of the time display from a breach sound and its corresponding spectrogram are shown in Fig. 3. The first major excursion was probably due to the dolphin's body impacting the water's surface. The second major excursion was probably caused by an air mass forced under the water by the impact of the dolphin on the water surface. Most of the energy produced by each breach was below 2 kHz, although some components extended as high as 14 kHz.

The dolphin slapping its tail on the water surface produced the next highest intensity sound. The source levels for each of ten tail slaps are shown in Fig. 4. The peak-to-peak source levels varied from about 166 dB to 175 dB re 1 μPa. The average peak-to-peak source level from tail slaps was 173 dB with a standard deviation of 2 dB re 1 μPa. Nine of ten tail slaps produced source levels within a range of about 4 dB. An example of a sound produced by the dolphin slapping its tail on the water surface and its corresponding spectrogram are shown in Fig. 5. Spectrograms of tail slaps indicate that most of the acoustic energy was below 2 kHz

The rms source levels for each of twenty-seven whistles are shown in Fig. 6. These trained whistles did not show a great deal of variation in source level. Most whistles occurred within a range of 10 dB with a minimum of 143 dB and a maximum of 153 dB re 1 μPa. The average rms amplitude of the whistles was 148.56 dB with a standard deviation of 2.29 dB re 1 μPa.

The envelope of two of the whistles in the time domain and the corresponding spectrogram are shown in Fig. 7. The envelope display shows the second whistle approximately 0.1 ms after the first whistle. Both whistles consisted of an upward sweeping, frequency-modulated signal increasing from 6 kHz to 20 kHz and then decreasing to about 6 kHz for the first whistle and 11 kHz for the second whistle.

Two jaw claps occurred and were serendipitously recorded when the dolphin approached the trainer. The time display and corresponding spectrogram of one jaw clap are shown in Fig. 8. Unfortunately, both jaw claps caused the DAT recorder to saturate and we can only say that both jaw claps were at least 172 dB re 1 μPa. However, our analysis indicates we captured most of the signal and that the actual peak-to-peak values were probably only several dBs greater than 172 dB.

Discussion

The sound pressure levels we measured from these four behaviors indicate that natural, low-frequency sounds produced by dolphins are louder than have typically been reported, but similar to those reported in a concurrent study by Finneran *et al.* (2000). Most previous reports have not included measurements from the typical dolphin-produced sounds from breaching and tail slap behaviors. All of the recorded source levels greatly exceed the hearing thresholds for the bottlenose dolphin (Johnson, 1996), at the appropriate frequencies and are therefore very likely heard by nearby, conspecific dolphins.

Whistles have long been assumed to have a communicative function in odontocete cetaceans (Evans, 1967; Dreher & Evans, 1964; Lilly, 1962; Sigurdson, 1993)

and are frequently heard and recorded in the wild. Whistles may be especially important at night when feeding reportedly takes place with some species, particularly the spinner dolphin (Norris *et al.*, 1994). Although the animal in this study was trained to produce the whistles, our recorded source levels near 149 dB are within the range of those previously recorded for bottlenose dolphins in the wild, or opportunistically gathered in captivity (Wartzog & Ketten, 1999). The frequencies of our recorded whistles also fit well into the ranges previously recorded for bottlenose dolphins (McCowan *et al.*, 1998), with most of the energy found between 2 and 20 kHz. However, most of the energy in these whistles occurs above the apparent 1 kHz upper hearing threshold for yellowfin tuna, *Thunnus abacares* (Iverson, 1967). Popper's recent (1997) look at clupeid American shad hearing demonstrates that although these fish display a typical fish audiogram, with peak sensitivity below 1 kHz like the tuna, they also possess a second area of hearing sensitivity within the range of peak frequencies for odontocete echolocation clicks (25 and 130 kHz).

Yellowfin tuna are known to associate with echolocating odontocete cetaceans and are the prey of echolocating false killer whales (Seifert, 1999), and probably other large cetaceans. If the clupeid American shad has developed a second area of hearing sensitivity in the ultrasonic range in response to predatory pressures, as suggested by Popper, we speculate that tuna may have also developed the ability to hear echolocation clicks between 25 and 130 kHz, in order to both localize symbiotic cetaceans and avoid predatory cetaceans We suggest a re-evaluation of yellowfin tuna, *Thunnus albacares*, hearing is needed in the frequency range of sounds produced by echolocating cetaceans.

The sounds produced by breaches, tail slaps and jaw claps were relatively loud at 176, 173, and 172 dB re 1 μPa, respectively, and all displayed a preponderance of energy below 2 kHz. These signals contained acoustic energies most easily heard by yellowfin tuna, *Thunnus albacares,* as demonstrated in the only known audiogram (Iverson, 1967). Certainly the sounds produced by the acrobatic leaps of the spinner dolphin (Norris *et al.*, 1994) should equal the tail slaps and breaches of our bottlenose dolphin and might be easily heard by the accompanying tuna.

References

Au, W.W.L. (1980) Echolocation signals of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in open waters. In R.G. Busnel & J.F. Fish, eds, *Animal Sonar Systems*, Plenum Press, New York, pp. 251-282.

Au, W.W.L. (1993) The Sonar of Dolphins. Springer-Verlag, New York.

Au, W.W.L. & Banks, T. (1998) The acoustics of snapping shrimp, *Synalpheus parneomeris,* in Kaneohe Bay. *Journal of the Acoustical Society of America,* 103(1): 41-47.

Au, W.W.L., Floyd, R.W., Penner, R.H. & Murchison, A.E. (1974) Measurement of echolocation signals of the Atlantic bottlenose dolphin *Tursiops truncatus* Montagu, in open waters.

Brill, R. L., Pawloski, J.L., Helweg, D.A., Au, W.W.L. & Moore, P.W.B. (1992) Target detection, shape discrimination, and signal characteristics of an echolocating false killer whale (*Pseudorca crassidens*).

Dierks, K.J., Trochta, R.T., Greenlaw, R.L. & Evans, W.E. (1971) Recording and analysis of echolocation signals. *Journal of the Acoustical Society of America*, 49, 1729-1732.

Dreher, J.J. & Evans, W.E. Cetacean communication. In W.N. Tavolga (Ed) *Marine Bioacoustics, Volume 2,* Pergamon, New York, pp 373-393.

Evans, W.E. (1967) Vocalization among marine mammals. In W.N. Tavolga (Ed), *Marine Bioacoustics, Volume 2*, Pergamon, New York , pp 159-186.

Evans, W.E. (1973) Echolocation by marine delphinids and one species of fresh water dolphin. *Journal of the Acoustical Society of America,* 54, 191-199.

Finneran, J.J., Oliver, C.W., Schaefer, K.M. & Ridgway, S.H. (2000). Source levels and estimated yellowfin tuna (*Thunnus albacares*) detection ranges for dolphin jaw pops, breaches, and tail slaps. *Journal of the Acoustical Society of America,* 107(1): 649-656.

Iverson, R.T.B. (1967) Response of yellowfin tuna (*Thunnus albacares*) to underwater sound. In Wm. N. Tavolga (Ed) *Marine Bioacoustics, Volume 2*, Pergamon Press, New York pp 105-122.

Johnson C.S. (1966) Auditory Thresholds of the bottlenose porpoise (*Tursiops truncatus,* Montague). U.S. Naval Ordnance Test Station Technical publication 4178, China Lake, California.

Lilly, J.C. (1962) Vocal behavior of the bottlenose dolphin. *Proceedings of the American Philosophical Society,* 106, 520-529.

McGowen, B., Reiss, D. & Gubbins, C. (1998) Social familiarity influences whistle acoustic structure in adult female bottlenose dolphins (*Tursiops truncatus*), *Aquatic Mammals,* 24.1, 27-40.

Nachtigall, P.E. & Moore, P.W.B. (1988) Animal Sonar: Processes & Performance. Plenum Press, New York.

Nachtigall, P.E., Au, W.W.L., Pawloski, J.L. and Roitblat, H.L. (1994) Animal echolocation and signal processing. *Oceans 94: Proceedings of the IEEE.*, I, 259-263.

National Research Council, Committee on Reducing Porpoise Mortality from Tuna Fishing (1992). *Dolphins & the Tuna Industry* (National Academy Press, Washington, DC).

Norris, K.S., Wursig, B., Wells, R. & Wursig, M. (1994) *The Hawaiian Spinner Dolphin.* University of California Press, Berkeley.

Perrin, W.F. (1969) The problem of porpoise mortality in the U.S. tropical tuna fishery. In: Thomas C. Poulter (ed), Proceedings of the Sixth Annual Conference on Biological Sonar & Diving Mammals, Stanford Research Institute, Palo Alto CA

Perrin, W.F., Warner, R.W., Fiscus, C.L. & Holts, D.B. (1973). Stomach contents of porpoise, *Stenella spp.*, and yellowfin tuna, *Thunnus albacares*, in mixed species aggregation, *Fisheries Bulletin.* **71**, 1077-1092.

Popper, A.N. (1997) A clupeid fish can detect ultrasound. *Nature, 389*, 341.

Schaefer, K.M. & Oliver, C.W. (2000). Shape, volume, and resonance frequency ofthe swimbladder of yellowfin tuna (*Thunnus albacares*), *Fish. Bull.* 98(2): 364-374.

Scott, M.D. & Cattanach, K.L. (1998). Diel patterns in aggregations of pelagicdolphins and tunas in the eastern Pacific, *Marine Mammal Science.* **14**, 401–428.

Seifert, D.D. (1999) *Personal Communication.* Poster presented at the 13th Biennial Conference on the Biology of Marine Mammals. Wailea, Maui, Nov 27-Dec 4.

Sigurdson, J. (1993) Frequency modulated whistles as a medium for communication with the bottlenose dolphin (*Tursiops truncatus*). In H.L. Roitblat, L.M. Herman, & P.E. Nachtigall, *Language & Communication, Comparative Perspectives.* Lawrence Erlbaum Associates, Inc, New Jersey, pp 156-172.

Thomas, J.A., Stoermer, M., Bowers, C., Anderson, L. & Garver, A. (1988) Detection abilities and signal characteristics of echolocating false killer whales (*Pseudorca crassidens*) in *Animal Sonar: Processes & Performance,* P.E. Nachtigall & P.W.B. Moore, Plennum Press, New York, pp 323-328.

Wartzog, D. & Ketten, D.R. (1999) Marine Mammal Sensory Systems, in *Biology of Marine Mammals* J.E. Reynolds III & S. A. Rommel, Smithsonian Institution Press, Herndon, Virginia. Pp 117-175.

Table 1.
Sounds Produced by Dolphins
(From Wartzog and Ketten, 1999)

Scientific Name	Common Name	Signal Type	Frequency Range (kHz)	Frequency Near Maximum Energy (kHz)	Source Level (dB re:1 μPa)
Stenella attenuata	Spotted dolphin	Whistles	3-21	7-18	-
Stenella clymene	Clymene dolphin	Whistles	6-19	-	-
Stenella ceruleoalba	Spinner dolphin	Whistles Pulse bursts	1-23	5-60	109-125
Stenella longirostris	Long-snouted spinner dolphin	Pulse Whistle Click	1-160 1-20 1-160	5-60	-
Stenella plagidon	Spotted dolphin	Whistles Clicks	5-20 1-8	7-18	-
Stenella styx	Gray's porpoise	Whistles	6-24	8-13	-
Steno bredanensis	Rough-toothed dolphin	Whistles Click	4-7 5-32	4-7	
Tursiops truncatus	Bottlenosed Dolphin	Whistles Clicks	1-24 10-160	4-15 110-130	218-228

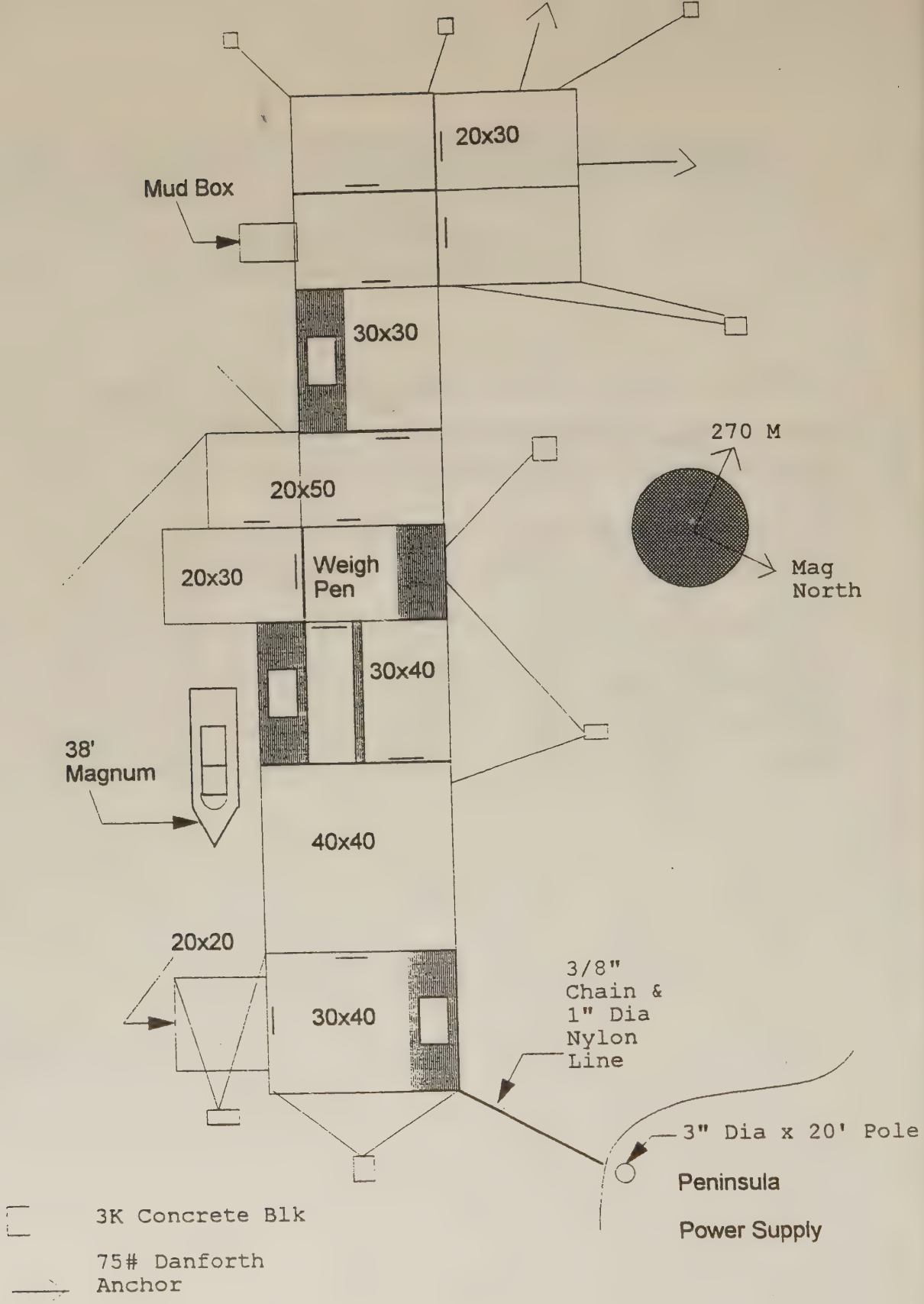

Figure 1. Overall layout of dolphin and whale pens at the Hawaii Institute of Marine Biology

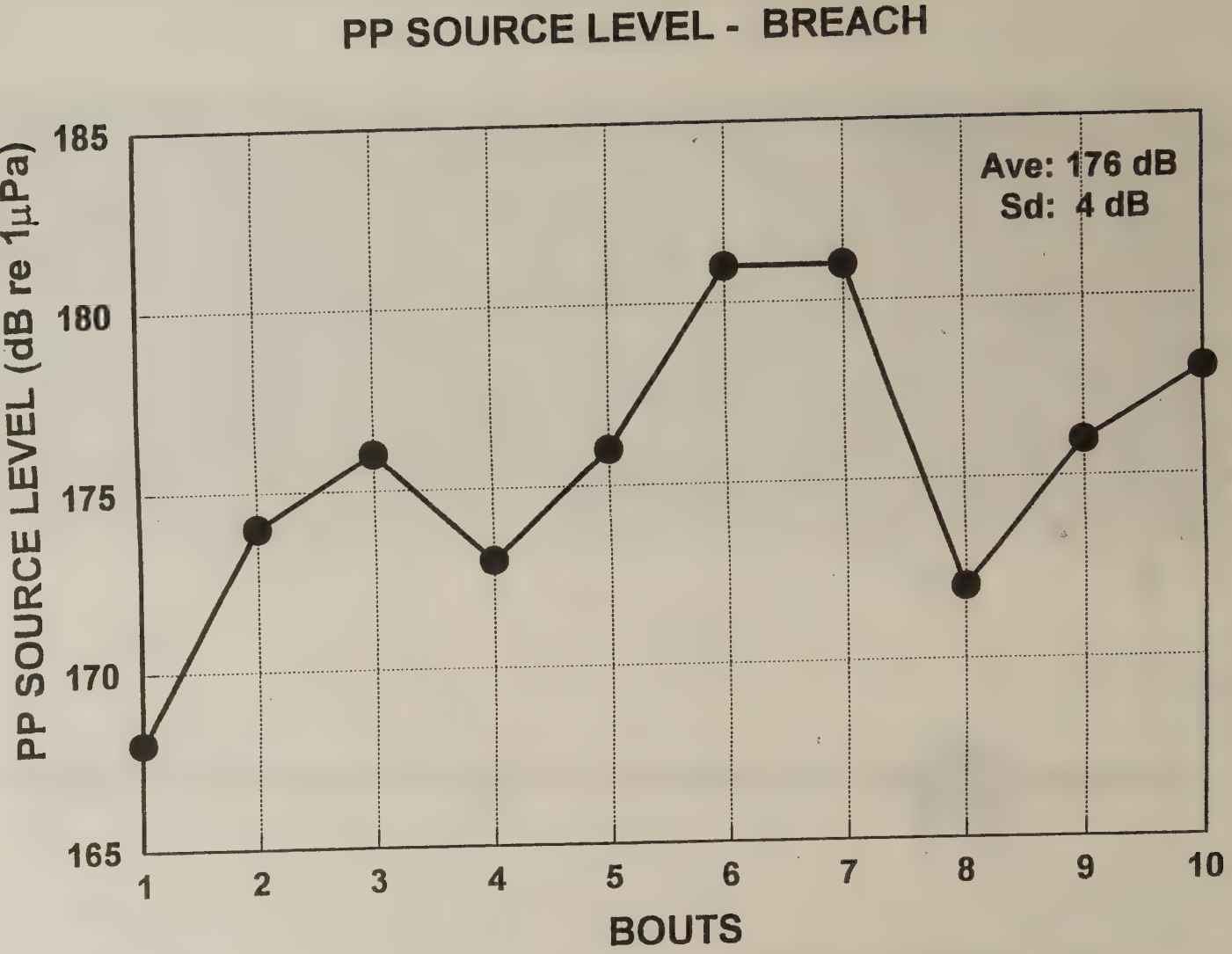

Figure 2. Peak–to-Peak source levels for ten dolphin breaches

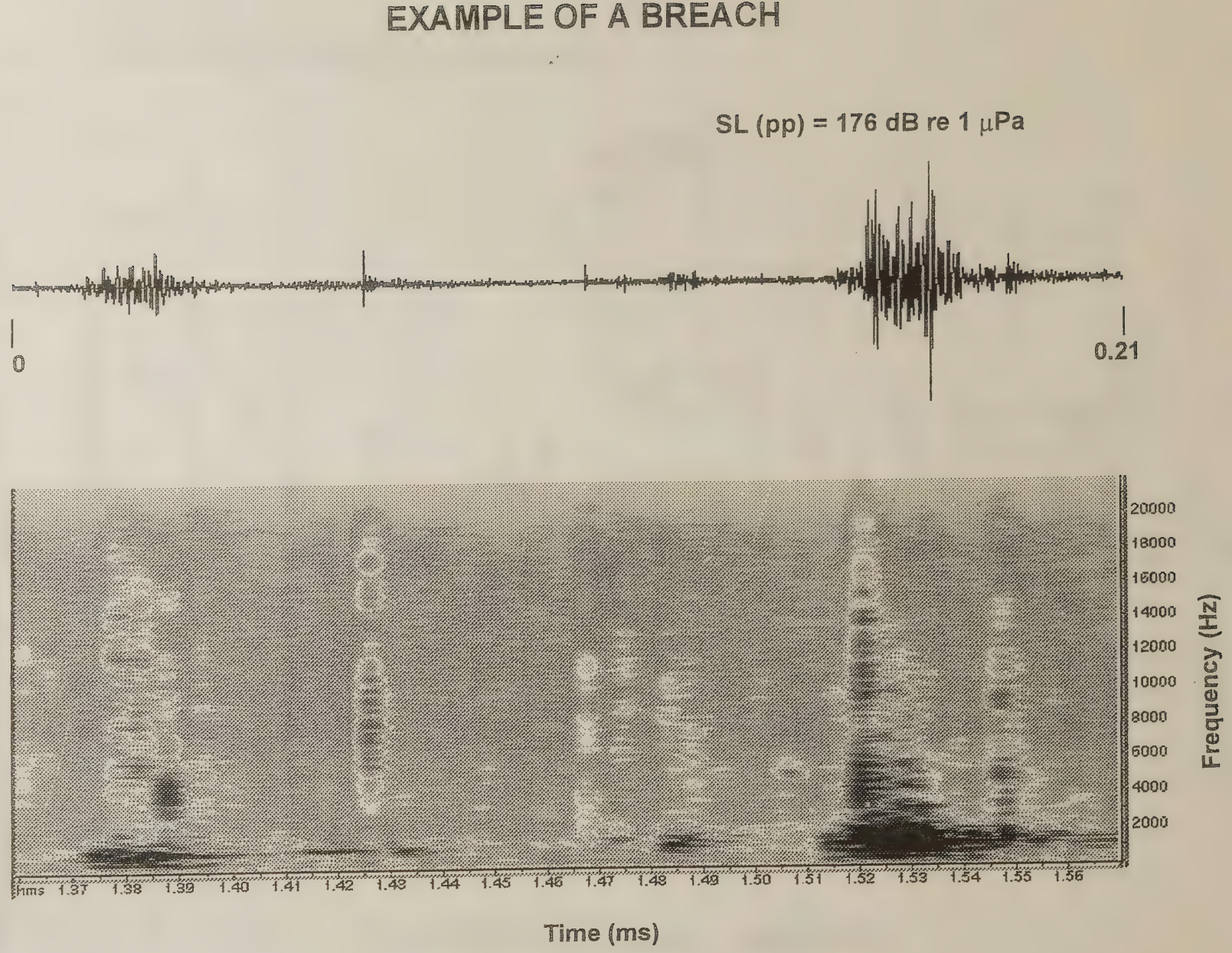

Figure 3. Time display of a breach sound and its corresponding spectrogram

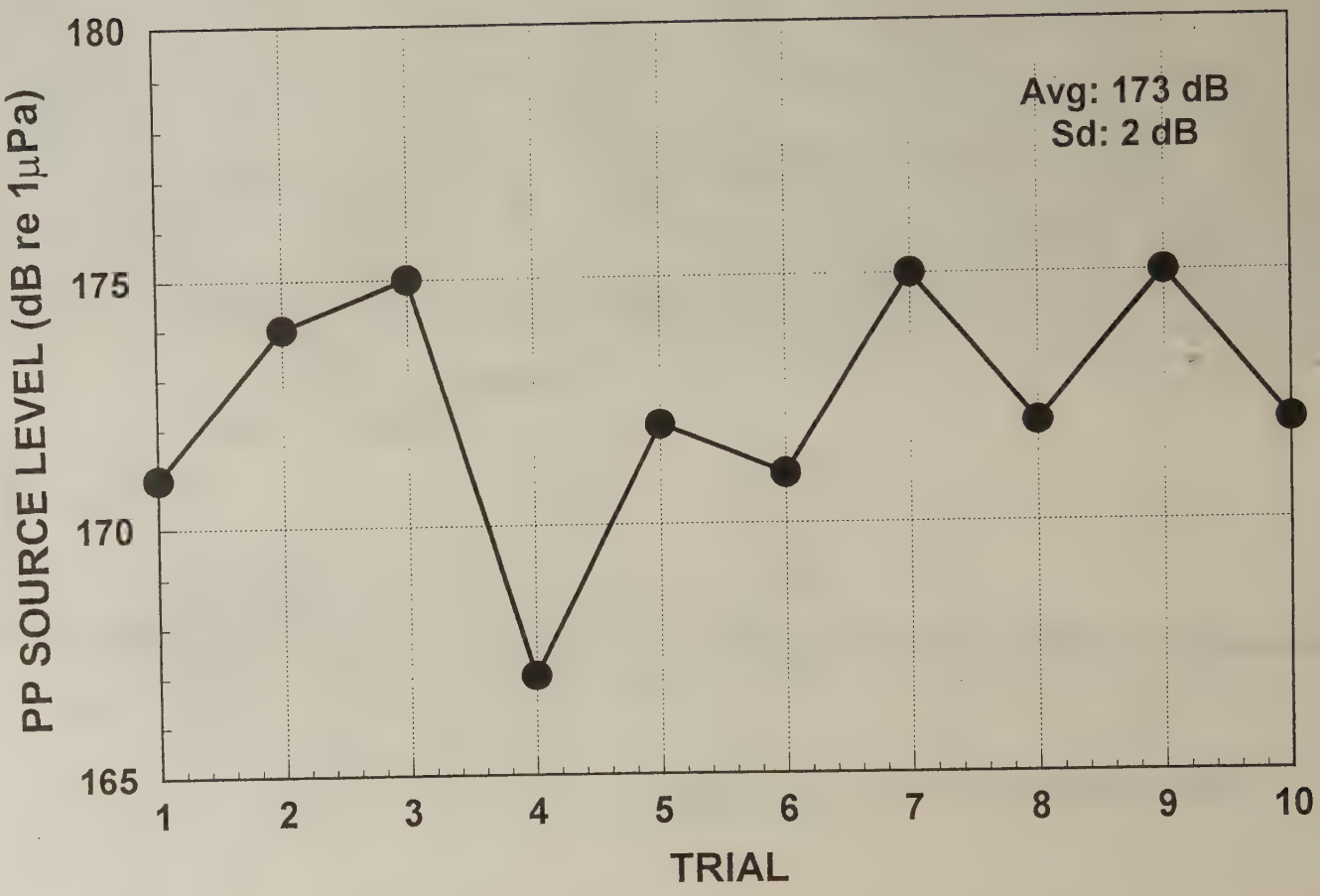

Figure 4. Peak-to-peak source levels from the sounds of 10 dolphin tail slaps

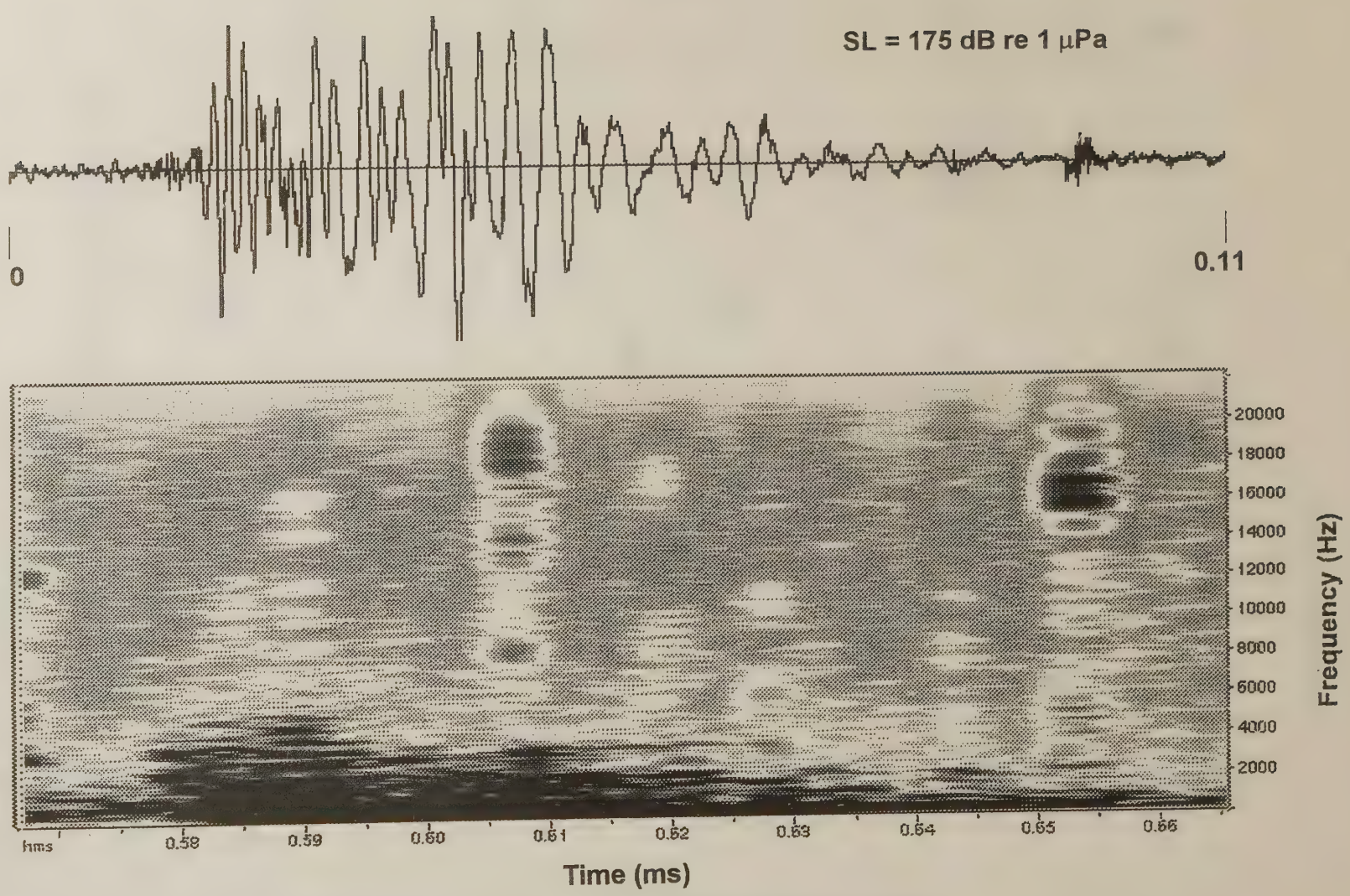

Figure 5. Time display of a dolphin slapping its tail and the corresponding spectrogram

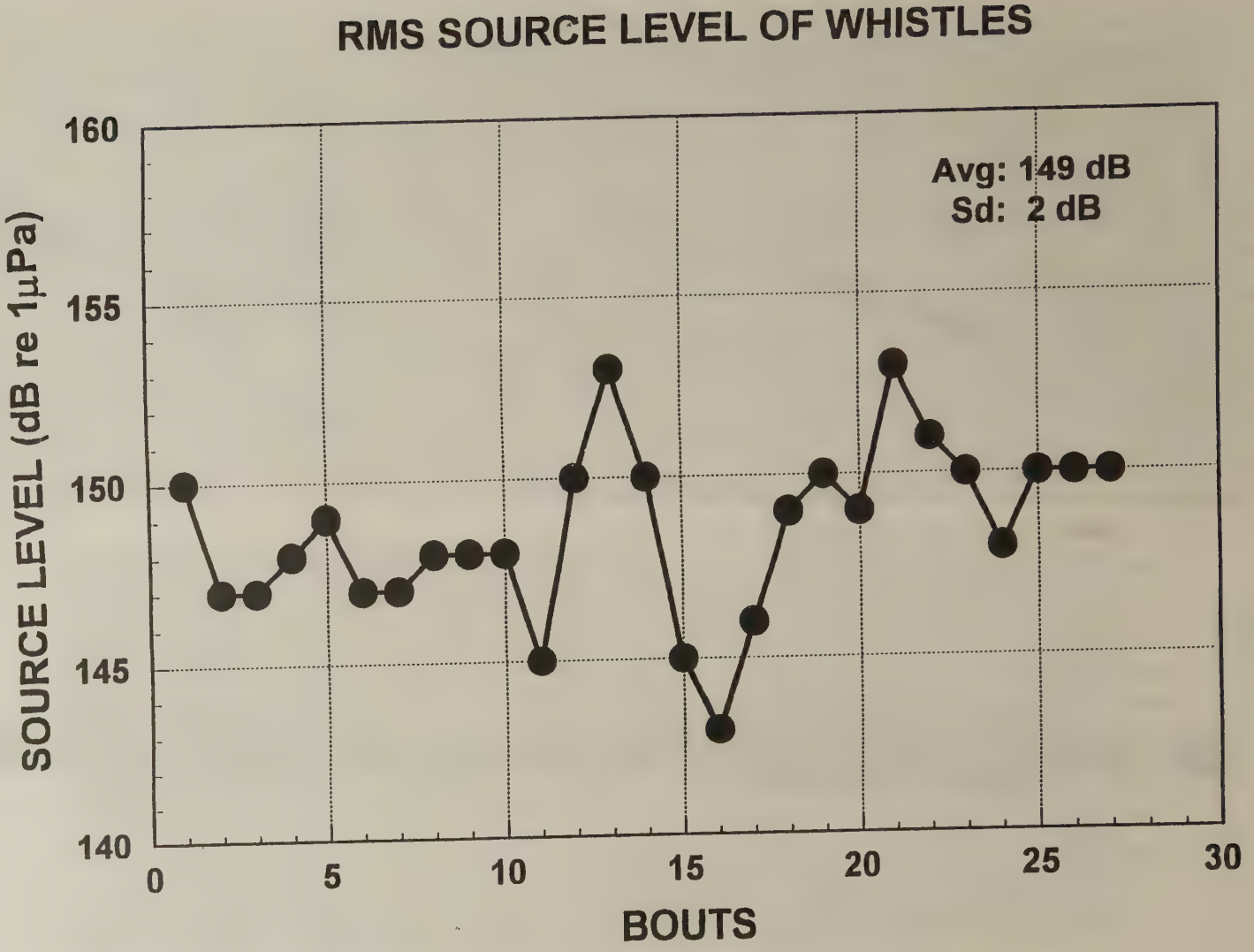

Figure 6. The RMS source level of the recordings of 27 dolphin whistles

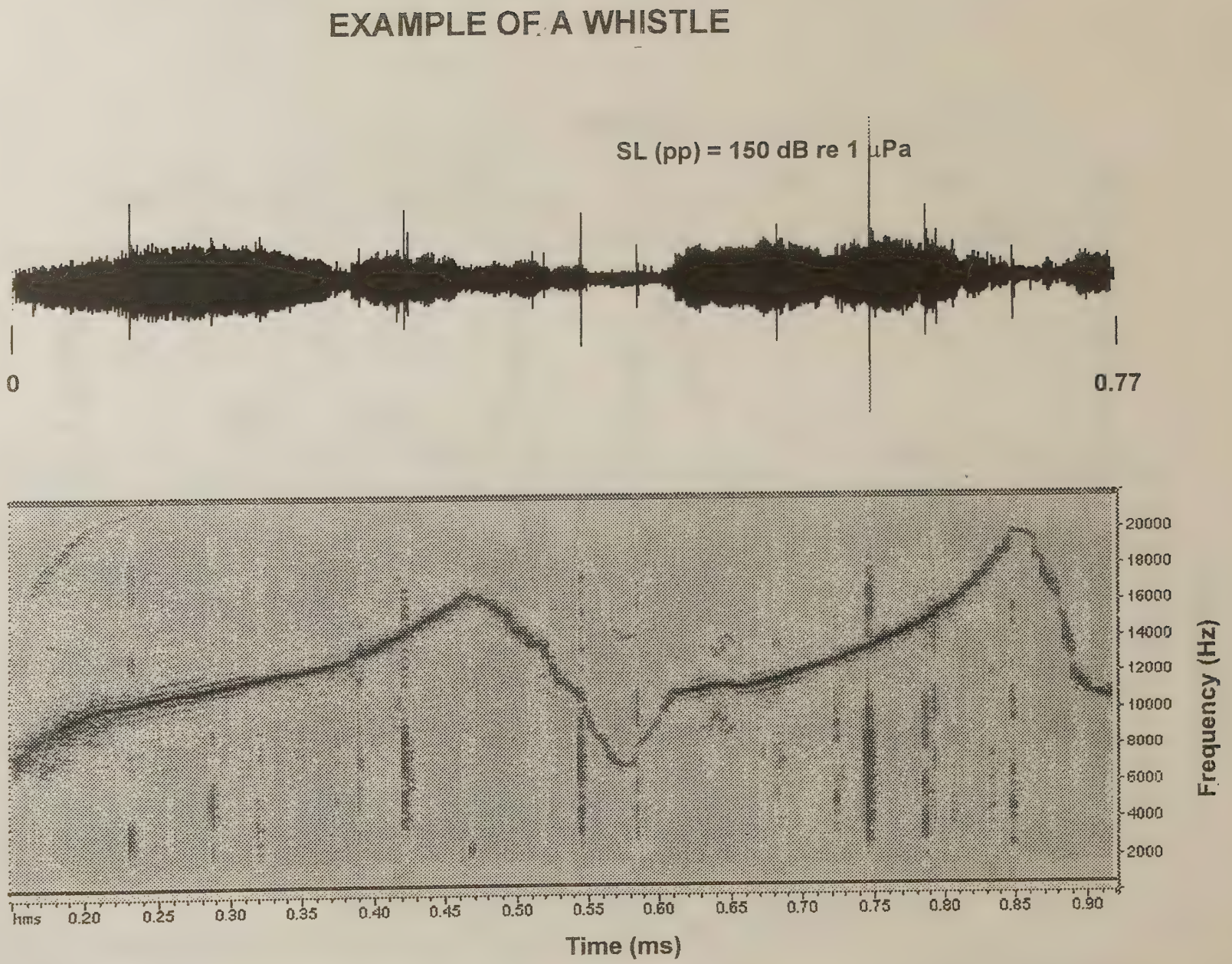

Figure 7. Time display of the envelope and corresponding spectrogram of two dolphin whistles

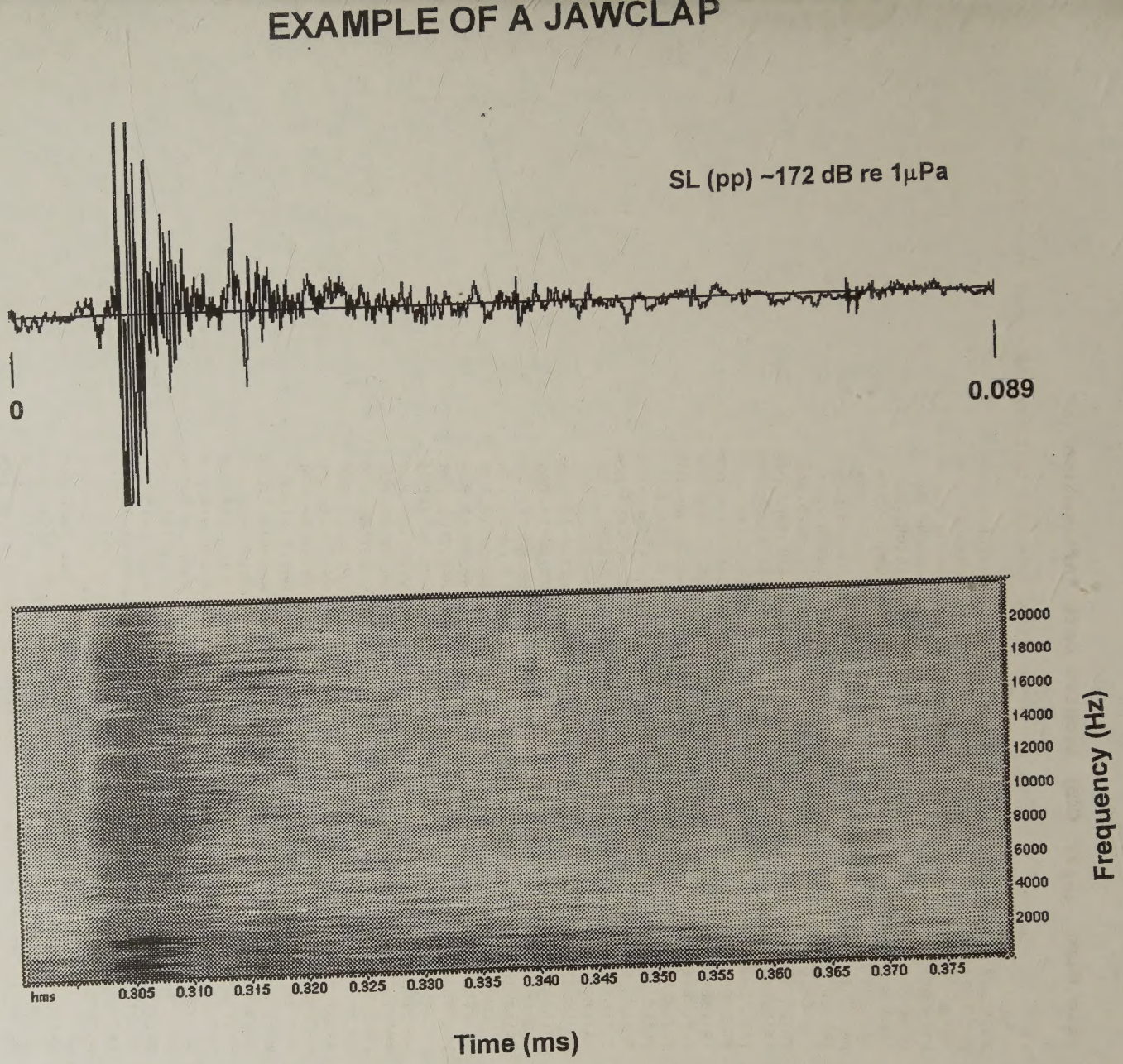

Figure 8. Time display and corresponding spectrogram of a recorded dolphin jaw-clap

Appendix 1. Digital files from recordings of breaches, tail-slaps, whistles, and jaw-claps obtained from a bottlenose dolphin on April 22 and May 4, 1999. These data are binary, 2-bytes per point digitized at 44.1 kHz with Cool-Edit. The custom-built hydrophone assembly has a sensitivity of -172 dB re V/µPa and is flat to 200 kHz.

File Name	Size (KB)	Archive Date	Information
1VP-P PCM	98,346	05-16-99	2:42p 1vp-p.pcm (calibration signal at 1 vpkpk and 1 kHz)
BREACH1# PCM	137,228	05-16-99	2:29p breach1#.pcm
BREACH2# PCM	138,228	05-16-99	2:30p breach2#.pcm
BREACH3# PCM	120,200	05-16-99	2:30p breach3#.pcm
BREACH4 PCM	192,320	05-16-99	2:31p breach4.pcm
BREACH5 PCM	221,368	05-16-99	2:35p breach5.pcm
BREACH6 PCM	343,570	05-16-99	2:36p breach6.pcm
BREACH7 PCM	221,368	05-16-99	2:36p breach7.pcm
BREACH8 PCM	179,298	05-16-99	2:37p breach8.pcm
BREACH9 PCM	174,290	05-16-99	2:38p breach9.pcm
BREACH10 PCM	231,386	05-16-99	2:39p breach10.pcm
TAILSL~1 PCM	84,614	05-16-99	2:05p tailslap1.pcm
TAILSL~2 PCM	87,344	05-16-99	2:06p tailslap2.pcm
TAILSL~3 PCM	60,048	05-16-99	2:07p tailslap3.pcm
TAILSL~4 PCM	117,158	05-16-99	2:11p tailslap4.pcm
TAILSL~5 PCM	139,126	05-16-99	2:11p tailslap5.pcm
TAILSL~6 PCM	132,718	05-16-99	2:12p tailslap6.pcm
TAILSL~7 PCM	109,834	05-16-99	2:13p tailslap7.pcm
TAILSL~8 PCM	114,412	05-16-99	2:13p tailslap8.pcm
TAILSL~9 PCM	77,800	05-16-99	2:13p tailslap9.pcm
TAILS~10 PCM	113,364	05-16-99	2:16p TAILS~10.PCM
TAILS~11 PCM	107,876	05-16-99	2:16p TAILS~11.PCM
TAILS~12 PCM	101,478	05-16-99	2:17p TAILS~12.PCM
TAILS~13 PCM	92,336	05-16-99	2:17p TAILS~13.PCM
TAILS~14 PCM	85,936	05-16-99	2:17p TAILS~14.PCM
TAILS~15 PCM	101,478	05-16-99	2:18p TAILS~15.PCM
TAILS~16 PCM	121,590	05-16-99	2:18p TAILS~16.PCM
WHISTLE1 PCM	138,426	05-16-99	2:43p WHISTLE1.PCM
WHISTLE2 PCM	95,402	05-16-99	2:44p WHISTLE2.PCM
WHISTLE3 PCM	102,884	05-16-99	2:44p WHISTLE3.PCM
WHISTLE4 PCM	115,980	05-16-99	2:44p WHISTLE4.PCM
WHISTLE5 PCM	109,430	05-16-99	2:45p WHISTLE5.PCM
WHISTLE6 PCM	68,276	05-16-99	2:45p WHISTLE6.PCM
WHISTLE7 PCM	100,078	05-16-99	2:45p WHISTLE7.PCM
WHISTLE8 PCM	213,246	05-16-99	2:46p WHISTLE8.PCM
WHISTLE9 PCM	92,022	05-16-99	2:47p WHISTLE9.PCM
WHISTL~1 PCM	155,730	05-16-99	2:47p whistle10.pcm
WHISTL~2 PCM	76,982	05-16-99	2:48p whistle11.pcm
WHISTL~3 PCM	113,260	05-16-99	2:48p whistle12.pcm
WHISTL~5 PCM	100,870	05-16-99	2:48p whistle13.pcm
WHISTL~4 PCM	103,524	05-16-99	2:49p whistle14.pcm
WHISTL~6 PCM	69,018	05-16-99	2:49p whistle15.pcm
WHISTL~7 PCM	42,472	05-16-99	2:50p whistle16.pcm
WHISTL~8 PCM	105,296	05-16-99	2:49p whistle17.pcm
WHISTL~9 PCM	137,150	05-16-99	2:50p whistle18.pcm
WHIST~10 PCM	80,520	05-16-99	2:51p whistle19.pcm
WHIST~11 PCM	130,956	05-16-99	2:51p whistle20.pcm
WHIST~12 PCM	98,218	05-16-99	2:51p whistle21.pcm
WHIST~13 PCM	99,986	05-16-99	2:52p whistle22.pcm
WHIST~14 PCM	104,410	05-16-99	2:52p whistle23.pcm
WHIST~15 PCM	104,410	05-16-99	2:52p whistle24.pcm
WHIST~16 PCM	95,562	05-16-99	2:52p whistle25.pcm
WHIST~17 PCM	86,714	05-16-99	2:53p whistle26.pcm
JAWCLAP1 PCM	73,622	05-16-99	2:58p jawclap1.pcm
JAWCLAP2 PCM	104,622	05-16-99	2:58p jawclap2.pcm